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Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise

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Abstract. The economy-wide implications of sea level rise in 2050 are estimated using a static computable general equilibrium model. This allows for a better estimate of the welfare effects of sea level rise than the common direct cost estimates; and for an estimate of the impact of sea level rise on greenhouse gas emissions. Overall, general equilibrium effects increase the welfare costs of sea level rise, but not necessarily in every sector or region. In the absence of coastal protection, economies that rely most on agriculture are hit hardest. Although energy is substituted for land, overall energy consumption falls with the shrinking economy, hurting energy exporters. With full coastal protection, GDP increases, particularly in regions with substantial dike building, but utility falls, least in regions that protect their coasts and export energy. Energy prices rise and energy consumption falls. The costs of full protection exceed the costs of losing land. The results also show direct costs – the usual method for estimating welfare changes due to sea level rise – are a bad approximation of the general equilibrium welfare effects; previous estimates of the economic impact of sea level rise are therefore biased.

Key words: computable general equilibrium, impacts of climate change, sea level rise

JEL classification: C68, D58, Q25

1. Introduction

Of the many impacts of climate change, sea level rise is often seen as one of the more threatening. The impacts of sea level rise are straightforward – more coastal erosion and sea floods, unless costly adaptation is undertaken – and unambiguously negative (unless one happens to be in the dike building sector). Sea level rise could have very substantial impacts in river deltas, and may wipe out entire islands and island nations (McLean et al. 2001).

Therefore, sea level rise figures prominently in assessments of the impacts of climate change, and the costs of sea level rise figures equally prominently in estimates of the costs of climate change. The majority of estimates of the economic damages of global warming rely on the methodology of direct costs, that is, damage equals price times quantity. The direct cost method ignores that the quantity change – say, the amount of land lost to sea level rise – may well affect the price – say, of coastal land. Furthermore, this method ignores that changes in one market – say, the market of land – have implications for all other markets. In this paper, we estimate and compare the direct costs, the partial equilibrium effects, and the general equilibrium effects of sea level rise.

The methodology can be briefly described as follows. Land losses due to sea level rise and costs of coastal protection are taken from the FUND database and model. Combined with scenarios of sea level rise, population growth and economic growth, this yields direct cost estimates as approximate welfare changes. Land losses or coastal protection are fed into GTAP-EF, to simulate general equilibrium effects on the world economy.

To our knowledge, two other papers have attempted this.[1] Deke et al. (2001) use the DART model to estimate economy-wide implications of sea level rise. Their study is restricted to the costs of coastal protection, ignoring land losses and its wider economic consequences. Deke et al. (2001) subtract the costs of coastal protection from total investment (equal to savings), thereby splitting investment between unproductive coastal protection and productive net investment. As they use a Solow-Swan growth engine to drive their recursive-dynamic CGE model, they essentially reduce the capital stock, and hence economic output and future consumption levels. Yet, in the short run, gross investment and final consumption are unaffected, thereby ignoring the stimulus to the engineering sector from extra investment in dikes and seawalls. Darwin and Tol (2001) use the FARM model, which is a static CGE. Their study is very similar to ours, but their CGE model is based on older data on national production and international trade. Furthermore, investments in coastal protection are modelled as a general loss of productive capital; Darwin and Tol (2001) do this instantaneously, while Deke et al. (2001) reduce the capital stock with a period's delay. Both Deke et al. and Darwin and Tol ignore the induced investment demand for of coastal protection, thus overstating the negative impact of sea level rise.[2] In this paper, we model coastal protection explicitly as an additional investment, thereby considering the effects induced by a different final demand in the economy. In contrast to Deke et al. and Darwin and Tol, we assume that investing in coastal protection crowds out consumption rather than other investment.[3] Like Darwin and Tol, but unlike Deke et al., we also consider a scenario in which coasts are not protected but land gets lost instead. Although FARM has a much richer representation of land and land use than does our model, this feature was not used by Darwin and Tol (2001); instead, land use was fixed, and each land type had the same *proportional* land loss. In our model, there is only one type of land. Like Darwin and Tol, we assume that part of this endowment disappears under the rising sea, and analyse the consequences for the economy. Like Darwin and Tol and Deke et al., we consider only a subset of the impacts of sea level rise, namely erosion, inundation, and coastal protection. There are other effects not considered here, for example, salt water intrusion, changes in tourist behaviour, or increased storm surges.

The structure of the paper is as follows. Section 2 presents our variant of the GTAP-E CGE model, called GTAP-EF. Section 3 discusses the implications of sea level rise. Section 4 discusses how these implications are brought into the CGE model. Section 5 presents the results. Section 6 concludes.

2. Model and Simulations

In order to assess the systemic, general equilibrium effects of sea-level rise, we made an unconventional use of a multi-country world CGE model: the GTAP model (Hertel 1996), in the GTAP-E version modified by Burniaux and Truong (2002), and subsequently extended by ourselves (GTAP-EF).[4] A concise description of the model structure, and of its basic assumptions, can be found in the appendix.

A CGE model provides a consistent and detailed description of an economic system, highlighting trade linkages between industries, regions and markets. We use a CGE model here to simulate the impact of exogenous changes in the composition of final demand and/or of available endowments of land in different countries.

The mathematical structure of a CGE model can be very complex. In particular, the GTAP model (and its variants) consists of hundreds of equations. See Hertel (1996) and http://www.gtap.org. A concise description of the model is provided in Appendix 1 of this paper. Typically, parameters in a CGE model are selected such that the model replicates the observed structure of the economy, as described in a calibration data-set, for a recent, reference year.

One problem of our application is given by the fact that we are interested in simulating changes occurring at some future dates, rather than at present time. Therefore, instead of relying on current calibration data, we base our exercise on a benchmark scenario of the world economic structure.

To this end, we derived baselines for the world economy at some selected future years (2010, 2030, 2050), using the methodology described in Dixon and Rimmer (2002). This entails inserting, in the model calibration data, scenario values for some key economic variables, to identify a hypothetical general equilibrium state for the future. This hypothetical equilibrium provides a benchmark, on which we build our comparative static exercise. This benchmark is subsequently compared with a counter-factual equilibrium, in which sea level impacts take place. Note that there is no explicit, dynamic process of adjustment.

To get the model baseline, we focused primarily on the supply side, by imposing estimates for future endowments of labour, capital, land, natural resources, as well as variations in factor-specific and multi-factor productivity, for the various industries and regions of the model.

Most of these variables (e.g., labour) are "naturally exogenous" in CGE models, so it is sufficient to change their levels from those of the initial calibration year of the model (1997) to those estimated for the future. In some other cases, we considered variables, which are normally endogenous in the model, and swapped them with exogenous variables.

We obtained estimates of the regional labour and capital stocks by running the G-Cubed model (McKibbin and Wilcoxen 1998). We took estimates of land endowments and agricultural land productivity from the IMAGE model version 2.2, scenario IPCC B1 (IMAGE 2001).

A different methodology was used for the natural resources stock variables. Values for these variables in the original GTAP data set are not from official statistics, but were calibrated to industry supply elasticities, taken from the literature (Hertel and Tsigas 2002). For this reason, we preferred to fix the price of the natural resources, and have it vary over time with GDP, and used the model to compute the corresponding stock levels.

3. Impacts of Sea Level Rise

In order to evaluate the impacts of sea level rise in the eight regions of GTAP-EF, we use information about potential losses of land and cost estimations of coastal protection. This information is exogenous to the CGE model, and it is used to generate the shocks in the simulation experiments. In reality, there will be a mix of protection and land loss; we here present the two extreme cases, avoiding the question how to trade-off land loss and protection. This section presents the sea level rise impact estimates that were used as inputs to the CGE model. Sea level rise would have a range of impacts. We here only include inundation and erosion. Flooding, salt water intrusion, and wetland loss are omitted for want of data.

For each region, Table I presents estimates of the potential dryland loss without protection. Our main source of information is the GVA (Global Vulnerability Assessment; Hoozemans et al. 1993), an update of work earlier done in the context of the Intergovernmental Panel on Climate Change

Table I. No protection scenario: main economic indicators

	Land (%)	Loss (km^2)	Direct (Mln $)	Costs (%GDP)	GDP (%)	Utility (%)	CO_2 (%)
A: Only land losses							
USA	−0.055	5000	102	0.0002	−0.002	−0.005	0.010
EU	−0.032	1015	187	0.0010	−0.001	−0.005	0.012
EEFSU	−0.020	4257	611	0.0100	−0.002	−0.006	0.005
JPN	−0.153	575	20	0.0001	−0.001	0.003	0.035
RoAx1	−0.006	1065	221	0.0030	0.000	0.008	0.015
EEx	−0.184	31847	15556	0.1010	−0.021	−0.015	−0.008
CHIND	−0.083	10200	324	0.0030	−0.030	−0.062	−0.024
RoW	−0.151	71314	13897	0.0600	−0.017	−0.014	−0.012

	Land (%)	Capital (%)	GDP (%)	Utility (%)	CO_2 (%)
B: Land and capital losses					
USA	−0.055	−0.055	−0.019	−0.020	−0.015
EU	−0.032	−0.032	−0.014	−0.015	−0.003
EEFSU	−0.020	−0.020	−0.008	−0.011	−0.001
JPN	−0.153	−0.153	−0.054	−0.041	−0.051
RoAx1	−0.006	−0.006	−0.002	0.000	0.017
EEx	−0.184	−0.184	−0.096	−0.077	−0.110
CHIND	−0.083	−0.083	−0.052	−0.046	−0.048
RoW	−0.151	−0.151	−0.076	−0.062	−0.092

Acronyms: USA, United States of America; EU, European Union; EEFSU, Eastern Europe and the Former Soviet Union; JPN, Japan; RoA1, Rest of Annex I (developed) countries; EEx, Energy exporters; CHIND, China and India; RoW, Rest of the World.

(IPCC CZMS 1990, 1992). The GVA reports impacts of a 1 m sea level rise scenario for all countries in the world. The GVA is not perfect, and its data are old. However, it is the only global and consistent database on sea level rise impacts available to date.

Dryland losses (in square kilometres) are not reported in the GVA, but they are, for selected countries, by Bijlsma et al. (1996), Nicholls and Leatherman (1995), Nicholls et al. (1995) and Beniston et al. (1998). Note that these are land losses due to erosion and inundation only. The GVA reports people-at-risk (in thousands of people), which is the number of people living in the one-in-1000-year flood plain, weighted by the chance of inundation. Combining this with the GVA's coastal population densities (in people per square kilometre), area-at-risk (in square kilometre) results. The exponent of the geometric mean of the ratio between area-at-risk and land loss for the 18 countries in Bijlsma et al. (1996), excluding wetland loss, was used to derive land loss for all other countries from the GVA's area-at-risk. This procedure introduces additional uncertainty. The review of the SCOR

Working Group 89 (1991) shows that beach erosion estimates due to climate change are not very accurate. Land losses thus estimated (Table IA, column 3) are expressed as a percentage of total land area (Table IA, column 2) using country areas reported by WRI (2002).

The GVA reports the costs of fully protecting the coast, with protection standards varying in an *ad hoc* but sensible way with population density and per capita income; particularly, coasts with few people in 1990 are *not* protected. Note that these costs are for protection against sea level rise only; changes in storminess are ignored. Protection costs are given for a 1 m sea level rise between 2000 and 2100, which is not very likely. However, costs are assumed to be linear in dike height (and so in sea level rise), and therefore readily scaled. The GVA reports the average annual investment over the century, which we annuitised.

Coastal protection may well imply a more rapid loss of coastal wetlands. The implications of this for the economy are here ignored, as these are difficult to quantify.

Direct costs are calculated as the amount of land lost times its value. This is a crude estimate of welfare loss, but the method is standard in the literature (Yohe 1990; Jansen et al. 1991; Nordhaus 1991, 1994; Rijsberman 1991; Cline 1992; Titus 1992; Fankhauser 1994; Nicholls and Leatherman 1995; Nicholls et al. 1995; Tol 1995, 1996, 2002; Yohe et al. 1995, 1996, 1999; Titus et al. 1998; Yohe and Schlesinger 1998).[5] The value of land is set at $250,000/km^2 in the USA, and varies with income density (GDP per area) using an elasticity of 0.53.[6]

The CGE has six regions, rather than all 166 coastal countries. Country-specific estimates of land loss, land area, expenditure on coastal protection, and GDP were aggregated to the regional level, the first two in square kilometres, the last two in dollars (using market exchange rates as in GTAP).

4. Including Impacts in the CGE Model

On the basis of the information about land loss and protection cost, we ran a set of comparative static exercises. These exercises are meant to capture the short run adjustments induced in the economic systems by the negative shocks, associated with climate change and sea level rise. To this end, we consider two polar cases.

In the "no-protection" scenario, we assume that no defensive expenditure takes place, so that some land is lost in terms of productive potential, because of erosion, flooding and salt water intrusion. This case can be easily accommodated in the model by exogenously reducing the endowment of the primary factor "land" in all countries, in variable proportions.[7]

In the "full-protection" scenario, on the contrary, we assumed that no land is lost because of sea-level rise, but this outcome requires some specific infrastructure investment. In practice, these measures can take the form of dike building or elevation, beach nourishment, and protection of freshwater resources. In the model, this translates into an exogenous increase of regional investment expenditure.

To fully assess the results of this simulation exercise, it is important to understand how we modified the mechanism of investment allocation in the GTAP-EF model, as well as the difference between our approach and some alternative modelling strategies.

Regional and global investments are endogenous variables in the GTAP framework. In the short run, the capital stock is given in each region, and investments are simply a demand component of GDP.[8]

Savings and investments are not equalized domestically, but at the global scale.[9] Savings are generated endogenously, because of the presence of a composite good "saving" in the utility function of each regional representative consumer. As a consequence, regional savings vary proportionally to the national income.[10]

A hypothetical "world bank" then collects savings and allocates investments, realizing the equalization of regional *expected* returns (as shown in Appendix 1).[11] In practice, since expected returns are linked to existing capital levels, investment flows are primarily directed towards regions in which capital stocks are relatively low. However, to account for imperfect international mobility of investment funds, and for the "home bias" in the portfolio selection of investors, a region-specific, calibrated elasticity parameter accounts for the actual degree of investment sensitivity to rate of return differentials.

For the "full protection" scenario, we made the regional investment variables exogenous, and fixed their level by adding the additional expenditure for coastal protection, in each region, to the initial investment level. To ensure the equalization of global savings and investment, we allowed for an endogenous adjustment of regional savings.[12]

Clearly, since global investment increases, so do global and hence domestic savings. To save more, each representative consumer has to consume less, thereby reducing her immediate utility. However, there is no direct link between regional consumption and investment; countries can run a foreign debt. Vulnerable regions would require more defensive expenditure. Part of this spending would be financed through foreign investment.

Our methodology significantly differs from the one adopted by Darwin and Tol (2001) and Deke et al. (2001). Darwin and Tol model defensive expenditure simply by assuming that some fraction of the capital, used in the production of goods and services, is converted to unproductive defensive infrastructure. The hypothesis of capital conversion is clearly unrealistic in the short run, but could be justified as an approximation of a long-run equilibrium in which defensive investment completely offsets productive investment, although there is no specific reason to believe that this offset would be one-for-one, Deke et al. (2001) subtracts investments in coastal protection from overall investment, without building up a "coastal protection capital" or even creating a demand for dike building. Our approach is different, and provides the advantage of accounting for the multiplicative effects of changes in the demand structure. For example, our model generates higher growth rates for the construction industry wherever new infrastructure is built.

5. Results

In this section, simulation results for the year 2050 are reported and commented, in terms of variation from the no-climate-change baseline equilibrium. Results for other reference years are qualitatively similar.

5.1. NO PROTECTION SCENARIO: LAND LOSS ONLY

Table IA shows the effects of sea level rise for the no-protection scenario, based on a uniform increase of 25 cm, which is well within the IPCC range of 10–40 cm for 2050 (Houghton et al. 2001). The table reports information about changes in the endowments of land resources, land losses in km^2, direct costs estimated as a product of physical land losses and land prices, direct costs as a fraction of regional GDP. All these data are inputs for the simulation exercise with the CGE model. The table also shows some results, in percentage variations, produced by the model: changes in GDP, in utility of the representative household (related to consumption levels), and in CO_2 emissions.

The fraction of land lost is quite small in all regions. Energy Exporting Countries (EEx) suffer the greatest loss, loosing 0.18% of their dry land, followed by Japan (JPN) and the Rest of the World (RoW), both with a 0.15% loss. The direct value of the land lost is large in absolute terms, but quite small if compared to GDP (EEx has the biggest value: 0.1% of GDP). Generally, developing regions – CHIND and RoW – experience direct losses higher than those of developed countries, because their economies are more agricultural and their relative land values are high. The same is true for EEx, which includes many African countries.

GDP falls in all regions, especially in CHIND (−0.030%), EEx (−0.021%) and RoW (−0.017%).[13] Two aspects are worth noting: first, general equilibrium effects influence the cost distribution. GDP losses for the Former Soviet Union (EEFSU), the Rest of Annex 1 (RoA1), EEx and RoW are lower than the direct cost of the lost land, whereas the opposite occurs to USA, EU, JPN and CHIND; in the case JPN, the GDP losses are even 10 times as large as the direct costs. Second, there is no direct relationship between the environmental impact and the economic impact. For instance, JPN exhibits the second highest amount of land lost, but the second smallest loss of GDP. CHIND, on the contrary, has the third smallest relative amount of land lost, but the highest cost in terms of GDP. This highlights the importance of conducting a general equilibrium analysis in this context, as substitution effects and international trade work as impact buffers or multipliers.[14] Recall that land is used only in agriculture. The impact on GDP is therefore largest in those regions in which agriculture is a large share of the economy, that is, the poorer regions CHIND, EEx and RoW. In addition, in richer economies, relative prices are such that is easier to substitute other inputs (particularly, fertilizer) for land.

Land is an essential factor in agriculture, so agricultural industries bear the biggest impact of the loss of land, as can be seen in terms of higher prices and lower production levels (Table II).

The regional impacts are illustrated in Table III. In general, lower GDP losses are associated with investment inflows, so it is important to clarify the

Table II. No protection scenario: price and production levels by industry

	Price index for world supply (% change w.r.t. baseline)	Quantity index for world supply (% change w.r.t.baseline)
Rice	0.484	−0.054
Wheat	0.314	−0.040
CerCrops	0.389	−0.042
VegFruits	0.360	−0.058
Animals	0.329	−0.045
Forestry	−0.102	−0.017
Fishing	−0.057	−0.020
Coal	−0.068	−0.012
Oil	−0.081	0.004
Gas	−0.066	0.001
Oil_Pcts	−0.075	0.004
Electricity	−0.058	−0.007
En.Int_in	−0.042	−0.013
Oth_ind	0.044	−0.033
MServ	−0.040	0.003
NMServ	−0.040	0.007

role played here by the investments. Land loss is a direct resource loss, a negative economic shock, which reduces income and consumption levels. The value of primary resources thus falls, with the exception of land, which is getting scarcer.

The international allocation of investments is driven by the relative price of the capital in each country. The higher the capital return, the higher the share of international investments flowing into a country. Investment is one component of GDP.

Changes in the price of capital are determined by two opposite effects. On one hand, the negative shock lowers the value of national resources, including capital. On the other hand, economies try to substitute land with capital. Capital supply is fixed in the short run, though, and the higher demand for capital translates into higher capital returns.

The fall in the relative price of capital is particularly strong in EEx, CHIND and RoW. In the model, lower returns on capital reduce the international capital inflow. This explains why regional GDP decreases

Table III. No protection scenario: industrial output and price of primary factors by region

	USA	EU	EEFSU	JPN	RoA1	EEx	CHIND	RoW
Industry output (% change w.r.t. baseline)								
Rice	−0.020	0.040	−0.013	−0.019	0.056	−0.086	−0.028	−0.073
Wheat	−0.051	−0.022	0.008	−0.259	0.043	−0.080	−0.033	−0.076
CerCrops	−0.020	0.037	0.060	−0.069	0.103	−0.116	−0.025	−0.083
VegFruits	−0.029	0.031	0.036	−0.078	0.087	−0.128	−0.050	−0.078
Animals	−0.026	−0.016	0.020	−0.035	0.022	−0.094	−0.077	−0.079
Forestry	−0.041	−0.024	−0.026	−0.031	−0.024	−0.015	−0.001	−0.011
Fishing	−0.007	−0.012	−0.017	−0.019	−0.033	−0.015	−0.036	−0.016
Coal	−0.009	−0.013	−0.008	−0.091	−0.058	0.016	−0.007	−0.012
Oil	−0.011	−0.024	−0.008	−0.064	−0.033	0.013	0.019	0.000
Gas	0.003	−0.036	−0.005	−0.042	−0.048	0.036	0.022	−0.014
Oil_Pcts	0.014	0.013	0.009	0.017	0.024	0.002	−0.034	−0.006
Electricity	0.001	−0.010	0.003	−0.010	−0.023	−0.007	−0.025	−0.006
En_Int_ind	−0.013	−0.015	−0.007	−0.040	−0.051	0.006	−0.003	−0.005
Oth_ind	−0.021	−0.017	−0.019	−0.010	−0.009	−0.083	−0.035	−0.071
Mserv	0.003	0.001	0.000	0.005	0.002	0.010	−0.036	0.011
NMServ	0.003	0.003	0.005	0.003	0.010	0.009	0.060	0.014
Investment	0.008	0.008	−0.013	0.031	0.022	−0.066	−0.172	−0.043
Price of primary factors (% change w.r.t. baseline)								
Land	0.534	0.514	0.532	1.019	0.607	0.804	0.467	0.802
Labour	−0.051	−0.051	−0.059	−0.002	−0.026	−0.123	−0.196	−0.108
Capital	−0.051	−0.048	−0.061	−0.001	−0.025	−0.127	−0.212	−0.112

relatively more than private consumption in these regions, as can be seen through the changes in the households utility index.

International trade also matters, through its effects on the terms of trade. Higher world prices for agriculture benefit net-exporters of agricultural goods (USA, RoA1, EEx), while lower prices for oil, gas, coal, oil products, electricity, and energy intensive products harm the net-exporters of energy products (EEx, EEFSU).

Labour, capital and *energy* substitute for the loss of land. At the same time, overall economic activity falls. In the OECD regions, the former effect dominates. The growth in market services raises the consumption of oil products, mainly by the transportation industries. Consequently, CO_2 emissions increase, despite the fall in GDP. In developing regions, the latter effect dominates: the decrease of GDP is associated with a decrease in CO_2 emissions.

5.2. NO PROTECTION SCENARIO: LAND AND CAPITAL LOSS

Above, we assume that there will be no investments in additional coastal protection, but that people do retreat. This assumes that sea level rise is slow and predictable, and that people anticipate loss of their capital goods by depreciating the last bit of capital just before inundation.

Table IB shows the results if we assume that invested capital is lost as well. As we have no geographically explicit representation of capital in relation to the shore, we assume that the same proportions of capital and land are lost.[15] This should change the distribution of the impacts, as developed countries have capital-intensive economies, in which agriculture plays a minor role.

GDP losses are obviously higher if together with land also capital is lost to sea level rise. The more capital-intensive developed economies are relatively harder hit by adding capital loss are than the more land-intensive developing economies. In general, however, the developing regions are more severely affected by climate change than the developed regions. We also see that those economies which get hit hardest, suffer disproportionally compared to those economies that suffer little consequences of sea level rise. The reason is that little impacted countries gain in their competitive position, as can be seen from the terms of trade. With capital losses added, CO_2 emissions fall almost everywhere.

5.3. TOTAL PROTECTION SCENARIO

In the protection scenario, there is no negative economic shock, since – by assumption – the stock of land resources is fully preserved.[16] However, the structure of final demand changes, because investment increases and household consumption decreases.

Table IV shows the additional expenditure for the various regions. See Section 3. Figures are relatively small in terms of GDP, but substantially higher than the value of land lost: the highest values are for RoA1 (0.80% of GDP) and EEFSU (0.33% of GDP), the lowest for USA (0.01% of GDP).[17] The high value for RoA1 results from a combination of a long coast exposed and high protection cost, particularly in Canada, Australia and New Zealand. To meet this extra demand for investment, all regions increase uniformly (+1.9%) their savings, reducing at the same time private consumption, especially in CHIND (−0.96%), JPN (−0.56%) and RoW (−0.35%). The impact on regional GDP is mixed: EU and JPN experience small losses (−0.02% and −0.01%, respectively), while all other regions gain slightly. EU and JPN attract little additional investment and are hit hard by the price increase of fossil fuels; USA also attracts little investment, but suffers less from the energy price increase.

Regional impacts are determined by the interplay of demand effects and changes in the terms of trade (see Table V). Because of the need to finance defensive infrastructure, the most vulnerable regions (RoA1, EEFSU) experience net investment inflows, stimulating a regional GDP growth. Note that this additional GDP does not offset the costs of dike building; GDP net of coastal protection is lower for all regions compared to the case without climate change.

Changes in the terms of trade are mainly driven by increases in the world price of energy products (see Table VI), benefiting energy exporting countries (EEx, EEFSU), and leading to a worldwide decrease of CO_2 emissions.

Table IV. Total protection scenario: main economic indicators

Region	Coastal protection expenditure		Investment induced by Coastal protection (% change w.r.t. baseline)	GDP (% change w.r.t. baseline)	Household utility index (% change w.r.t. baseline)	CO_2 emissions (% change w.r.t. baseline)
	1997 million US$	% of GDP				
USA	5153	0.010	0.151	0.001	−0.206	−0.069
EU	11,213	0.025	0.302	−0.022	−0.296	−0.160
EEFSU	23,076	0.332	3.179	0.049	0.033	−0.133
JPN	7595	0.032	0.242	−0.009	−0.605	−0.344
RoA1	71,496	0.799	9.422	0.103	−0.009	−0.130
EEx	363,856	0.185	2.235	0.015	−0.223	−0.069
CHIND	11,747	0.106	1.254	0.003	−0.889	−0.116
RoW	38,808	0.148	1.817	0.009	−0.310	−0.115

Table V. Total protection scenario: industrial output and price of primary factors by region

	USA	EU	EEFSU	JPN	RoA1	EEx	CHIND	RoW
Industry output (% change w.r.t. baseline)								
Rice	0.061	−0.140	−0.160	0.595	−0.560	−0.073	0.165	−0.031
Wheat	0.045	0.045	−0.073	−0.378	0.161	−0.061	0.097	−0.015
CerCrops	−0.007	−0.017	−0.095	−0.061	−0.021	0.025	0.164	0.030
VegFruits	−0.030	−0.060	−0.082	−0.185	−0.095	−0.045	−0.037	−0.025
Animals	0.140	0.104	−0.074	0.399	−0.478	−0.029	−0.207	−0.027
Forestry	0.091	0.112	−0.287	0.209	−0.783	−0.141	−0.273	−0.160
Fishing	0.157	0.049	−0.166	0.454	−0.854	−0.099	−0.207	−0.096
Coal	0.097	0.113	−0.244	0.876	−1.236	−0.059	0.019	0.016
Oil	0.063	0.120	−0.374	0.387	−0.691	−0.102	−0.092	−0.056
Gas	0.231	0.556	−0.419	0.177	−1.234	−0.071	0.020	−0.060
Oil_Pcts	−0.121	−0.114	−0.136	−0.251	0.139	−0.101	−0.413	−0.158
Electricity	0.056	0.088	−0.249	0.042	−1.204	−0.119	−0.116	−0.109
En_Int_ind	0.259	0.269	−0.823	0.573	−2.470	−0.204	0.084	−0.132
Oth_ind	0.227	0.199	−0.177	0.655	−1.364	−0.104	0.336	−0.027
MServ	−0.043	−0.055	0.257	−0.177	0.725	0.132	0.019	0.078
NMserv	−0.093	−0.074	−0.004	−0.117	−0.092	−0.121	−0.382	−0.116
Price of primary factors (% change w.r.t. baseline)								
Land	0.499	0.356	−0.359	2.098	−1.467	−0.101	−0.713	−0.071
Labour	−0.154	−0.090	0.833	−0.536	1.376	0.251	0.111	0.130
Capital	−0.144	−0.103	0.806	−0.528	1.275	0.253	0.156	0.140

Variations in regional GDP are not particularly informative for a comparison of the two scenarios, but changes in aggregate private consumption (household utility index) provide a rough estimate of the welfare impact in the two cases. From this perspective, there are significant differences in both aggregate and distributional effects. See Figure 1.

At an aggregate level, effects are stronger, and globally an order of magnitude more negative, in the total protection scenario than in the no protection case. This seems to suggest that it would be better, economically speaking, to avoid a full protection policy (although an optimal protection rate likely lies between the two extremes).

There are also substantial distributional differences. Asian regions – JPN and CHIND – are especially worse off in these circumstances in the protection scenario. EEFSU is the only region with short-term utility gains, because it receives the second highest influx of investments in coastal protection, and because it benefits from the increased value of energy exports. The utility loss of RoA1 is relatively small, because it receives so much investment for coastal protection.

Table VI. Total protection scenario: price and production levels by industry

	Price index for world supply (% change w.r.t. baseline)	Quantity index for world supply (% change w.r.t. baseline)
Rice	0.011	0.094
Wheat	0.051	0.025
CerCrops	0.085	0.022
VegFruits	−0.103	−0.043
Animals	0.022	−0.011
Forestry	−0.064	−0.177
Fishing	0.038	−0.052
Coal	0.122	−0.109
Oil	0.080	−0.143
Gas	0.283	−0.180
Oil_Pcts	0.056	−0.154
Electricity	0.034	−0.080
EnInt_in	0.024	−0.002
Oth_ind	−0.002	0.136
MServ	−0.015	0.013
NMserv	−0.016	−0.102

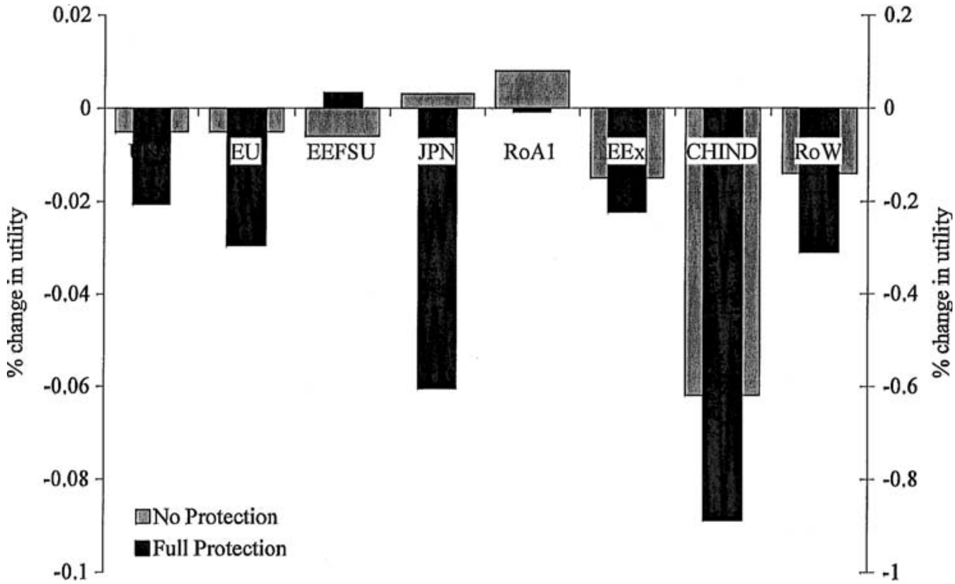

Figure 1. The change in household utility index with respect to the baseline for the case without protection (wide, light bars; left axis) and the case with full protection (narrow, dark bars; right axis).

6. Discussion and Conclusion

We estimate the economy-wide effects of sea level rise using a global computable general equilibrium model with eight regions. We do so for the year 2050, assuming a 25 cm sea level rise. Other sea level scenarios are of course possible, but would not lead to a greater qualitative insight. Alternative economic scenarios are also possible. In our set-up, the crucial variable in the no protection scenario is the importance of agriculture in the economy. If agriculture is more important, the economic impact of sea level rise is greater. In the full protection scenario, the international capital market is crucial. As this market is only rudimentary in our static CGE, further analysis is deferred to future research.

We distinguish two scenarios for adaptation. In the first, coasts are unprotected and lands are lost to the sea. In the second scenario, coasts are fully protected. Optimal adaptation will lie somewhere in between these two extremes. Compared to earlier studies, our treatment of the impact of sea level rise is more complete as we study both coastal protection and land loss, and our treatment of investments in coastal protection is more realistic, as we also include the induced demand from investments. Secondary but potentially important impacts related to sea level rise are not considered here.

On balance, the general equilibrium effects add to the direct costs of land loss or investments in coastal protection. This is because the loss of land or investment deflates the entire economy. The distribution of the general equilibrium effect is very different from the distribution of land losses or coastal protection, and the distributional effects of land losses and coastal protection also differ substantially.

For the scenario without coastal protection, the general equilibrium effects are strongest in economies that rely most on agriculture. Although energy is substituted for the loss of land, the price of energy demand falls with the shrinking economy, hurting energy exporters.

For the other scenario with coastal protection, GDP generally expands as we force the model to additionally invest in coastal protection. These investments are financed by the global capital market. As a result, utility falls, least in those regions with most dike building, and utility falls most in Asia.

Like Darwin and Tol (2001) and Deke et al. (2001), we find that direct costs underestimate the true welfare losses and get the regional distribution wrong at that. A detailed comparison of results is unfortunately impossible. The earlier studies report aggregate results only, in different units at different times, and for one scenario only (optimal protection/land and capital lost in the case of Darwin and Tol; full protection in the case of Deke et al.); Deke et al. also use different input data, and a recursive-dynamic rather than a static model.

This paper shows that the economy-wide, indirect effects of the impacts of climate change are, first, substantial compared to the direct effects and, second, distributed differently. The direct cost method still dominates the climate change impact literature (Smith et al. 2001). As such, this paper adds to our knowledge about climate change impacts.

Nonetheless, more research needs to be done. First, sea level rise is only one of the many impacts of climate change. In two companion papers, we look at health (Bosello et al. 2006) and tourism (Berrittella et al. 2006). Furthermore, we do not even include all impacts of sea level rise; particularly, flooding, wetland loss and saltwater instrusion are ignored. The analysis here should be repeated with more up-to-date and more comprehensive estimates of sea level rise, as soon as these become available. Second, we use a static CGE, limiting the analysis to the short-term effects. Fankhauser and Tol (2005) study the impact of climate change in one-sector growth models, also finding that the indirect economic effects may be just as important as the direct costs. Third, the shocks imposed are relatively crude; the allocation of land is underdeveloped in GTAP, so that adaptation is limited; investment in coastal protection does not crowd out other investment; and the trade-off between coastal protection and land loss is not made. Fourth, although we find that carbon dioxide emissions change, we do not feed this back into the climate scenario. All this is postponed to future research.

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Notes

1. A third paper, Kemfert (2002), includes sea level rise in a wider range of impacts, but does not separate out the effects of sea level rise. See Roson and Tol (2006).
2. This is most easily seen in terms of changes in GDP. One way of computing GDP is through the sum of service values of primary resources. If capital stock is cut, this translates into a direct GDP loss. On the other hand, GDP can also be expressed as the sum of final demand components. If additional investment is required, and financed through compensating reductions in consumption or other investment, GDP can only vary as a consequence of second order (systemic) effects.
3. Dike building crowding out consumption and dike building crowding out investment are the two extreme assumptions. It would be interesting to contrast the two assumptions with the same model and assumptions. Unfortunately, our static CGE model does not allow for the analysis of shocks to investment. In the short run, if one type of investment replaces other investments, while keeping total investment unchanged, macroeconomic effects are likely to be negligible, and only related to possible changes in the cost structure of investment demand (for which macro data is not usually available).
4. A more complete description of the modelling approach can be found in Roson (2003).
5. Turner et al. (1995) use the discounted flow of GDP per square kilometre as an indicator for land value. Broadus (1996) also uses this approach.
6. This elasticity is estimated using data for the states of the USA; data are taken from US DoC (1992, 1993).
7. In the GTAP model, land is used as a production factor only in agricultural industries. Of course, land is necessary for other productive activities but, normally, the service cost of land is negligible in total production costs.
8. In most dynamic CGE formulations, capital stock is updated in each period, on the basis of depreciation and investment realized one period in advance.
9. The condition equalizing global saving and investment is the redundant equation in the Walras general equilibrium system.
10. Regional saving shares are calibrated model parameters, different for each region.
11. The interested reader will find a complete description of the investments allocation mechanism in Hertel (1996). Here, it is sufficient to say that this mechanism attains a compromise between a neo-classical arbitrage and a home-biased asset allocation.
12. Assuming that all regional investments increase by the same percentage, the model calculates the implied changes in the shares of national income devoted to savings.
13. Note that the change in the *net* domestic product is the sum of the change the *gross* domestic product (Table IA, column 6) and the direct costs of land loss (Table IA, column 5). This implies that, overall, the direct cost method underestimates the true costs of land loss, a point also noted by Darwin and Tol (2001).
14. Substitution reduces the economic impact of land scarcity by partly replacing the land factor with other inputs. International trade works to the opposite direction: land scarcity deteriorates the relative competitiveness of land-intensive industries and regions.
15. This is, by no mean, a realistic assumption. This simulation run should therefore be interpreted as a sensitivity analysis.
16. Recall that this does not hold for wetlands.
17. Indeed, using cost-benefit analysis, Fankhauser (1994) and Yohe et al. (1996) find that it is optimal to protect most but not all populated coasts. Note that our Table IV cannot be readily compared to Table V in Darwin and Tol (2001) as we show results for total protection, whereas Darwin and Tol (2001) show results for partial (optimal) protection.

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Appendix 1

A CONCISE DESCRIPTION OF GTAP-EF MODEL STRUCTURE

The GTAP model is a standard CGE static model, distributed with the GTAP database of the world economy (http://www.gtap.org).

The model structure is fully described in Hertel (1996), where the interested reader can also find various simulation examples. Over the years, the model structure has slightly changed, often because of finer industrial disaggregation levels achieved in subsequent versions of the database.

Burniaux and Truong (2002) developed a special variant of the model, called GTAP-E, best suited for the analysis of energy markets and environmental policies. Basically, the main changes in the basic structure are:

– energy factors are taken out from the set of intermediate inputs, allowing for more substitution possibilities, and are inserted in a nested level of substitution with capital;

– database and model are extended to account for CO_2 emissions, related to energy consumption.

The model described in this paper (GTAP-EF) is a further refinement of GTAP-E, in which more industries are considered. In addition, some model equations have been changed in specific simulation experiments. This appendix provides a concise description of the model structure.

As in all CGE models, GTAP-EF makes use of the Walrasian perfect competition paradigm to simulate adjustment processes, although the inclusion of some elements of imperfect competition is also possible.

Industries are modelled through a representative firm, minimizing costs while taking prices are given. In turn, output prices are given by average production costs. The production functions are specified via a series of nested CES functions, with nesting as displayed in the tree diagram of Figure A1.

Notice that domestic and foreign inputs are not perfect substitutes, according to the so-called "Armington assumption", which accounts for – amongst others – product heterogeneity.

In general, inputs grouped together are more easily substitutable among themselves than with other elements outside the nest. For example, imports can more easily be substituted in terms of foreign production source, rather than between domestic production and one specific foreign country of origin. Analogously, composite energy inputs are more substitutable with capital than with other factors.

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labour, capital). Capital and labour are perfectly mobile domestically but immobile internationally. Land and natural resources, on the other hand, are industry-specific.

This income is used to finance the expenditure of three classes of expenditure: aggregate household consumption, public consumption and savings (Figure A2). The expenditure shares are generally fixed, which amounts to saying that the top-level utility function has a Cobb-Douglas specification. Also notice that savings generate utility, and this can be interpreted as a reduced form of intertemporal utility.

Public consumption is split in a series of alternative consumption items, again according to a Cobb-Douglas specification. However, almost all expenditure is actually concentrated in one specific industry: Non-market Services.

Private consumption is analogously split in a series of alternative composite Armington aggregates. However, the functional specification used at this level is the Constant Difference in Elasticities form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods.

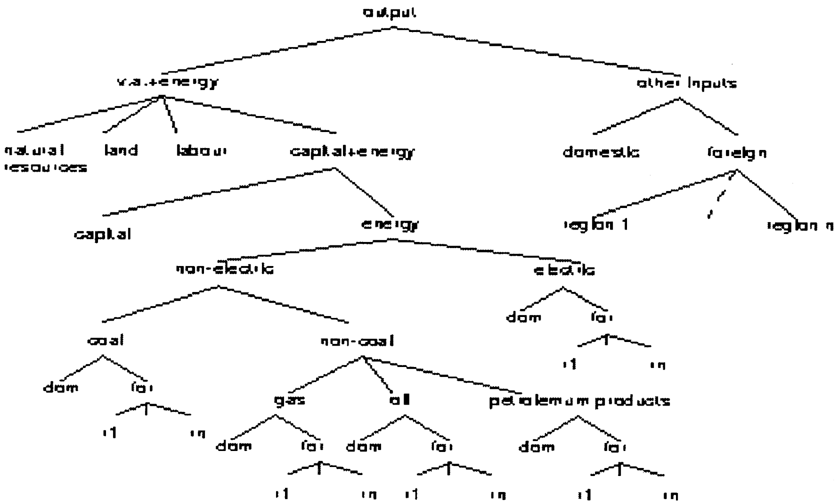

Figure A1. Nested tree structure for industrial production processes.

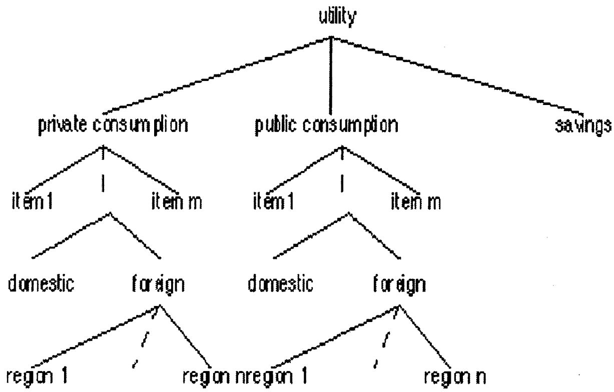

Figure A2. Nested tree structure for final demand.

In the GTAP model and its variants, two industries are treated in a special way and are not related to any country, viz. international transport and international investment production.

International transport is a world industry, which produces the transportation services associated with the movement of goods between origin and destination regions, thereby determining the cost margin between f.o.b. and c.i.f. prices. Transport services are produced by means of factors submitted by all countries, in variable proportions.

In a similar way, a hypothetical world bank collects savings from all regions and allocates investments so as to achieve equality of expected future rates of return. Expected returns are linked to current returns and are defined through the following equation:

$$r_s^e = r_s^c \left(\frac{ke_s}{kb_s} \right)^{-\rho}$$

where: r is the rate of return in region s (superscript e stands for expected, c for current), kb is the capital stock level at the beginning of the year, ke is the capital stock at the end of the year, after depreciation and new investment have taken place. ρ is an elasticity parameter, possibly varying by region, determining the sensitivity of regional investments to rate of returns differentials. When the model is calibrated, all variables on the right-hand side are known. Therefore, to be consistent with the assumption of equalization of expected returns, this elasticity parameter ρ is estimated accordingly. In this way, investment funds are modelled as imperfectly mobile in international markets.

Future returns are determined, through a kind of adaptive expectations, from current returns, where it is also recognized that higher future stocks will lower future returns. Regional investments determine the stocks of capital at the end of each period, so that the arbitrage condition on expected returns is satisfied.

In this way, savings and investments are equalized at the international but not at the regional level. Because of accounting identities, any financial imbalance mirrors a trade deficit or surplus in each region.